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ENGINE PERFORMANCE DETERIORATION

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EFFECT OF FLIGHT LOADS ON TURBOFAN ENGINE

PERFORMANCE DETERIORATION

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ABSTRACT

A significant percentage of high-bypass-ratio turbofan engine performance deterioration is caused by an increase in operating clearance between fan/compressor and turbine blades and their outer air seals. These increased clearances result from rubs induced by a combination of engine power transients and aircraft flight loads. An analytical technique for predicting the effect of quasi-steady state aircraft flight loads on engine performance deterioration has been developed and is presented. Thrust, aerodynamic and inertia loads are considered. Analytical results are shown and compared to actual engine test experience.

INTRODUCTION

The current and projected high cost of fuel for gas turbine engines places a premium on incorporation of design features which increase the operating efficiency of aircraft propulsion systems. One such feature, universally recognized to be of major importance, is the maintenance of tight operating clearances between static and rotating components of flow-path seals. In practice, this is difficult to accomplish since the individual seal components and their supporting structures experience wide excursions in temperatures,

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rotational speeds, and other loadings at different points in the flight cycle. These conditions give rise to relative deflections that can lead to contact, wear, and increased clearances between seal parts. Early gas turbine engines accounted for these time-varying loads and associated deflections as part of the standard design process, and attempts were made to tune rotor and case growths such that tight clearances would occur during steady-state operation without introducing damaging rubs during transient conditions such as takeoff and landing. In view of the ready availability of inexpensive fuel and other factors, designs which suffered a loss of a few percent in efficiency after a year or two in service were considered adequate at that time.

Today's situation is quite different, as a consequence of two factors. First, fuel costs have more than doubled and are expected to continue to rise. Second, higher bypass ratio engines with their lightweight, flexible structures are more susceptible to structural deformations which can cause tight seal clearances to be increased by rubs.

This paper describes progress that has been made toward development of a comprehensive analytical procedure for predicting the effects of flight loads on gas turbine performance deterioration. The flight loads considered are steady-state aerodynamic, and steady-state inertia loads including gyroscopic moments on the rotors resulting from aircraft pitch and yaw motions. Internal engine loads due to thrust, thermal loads, and engine thrust reverse loads produced during engine operation are also included in the procedure.

The damage mechanism considered is wear of flow-path outer air seals due to interference of rotating (blade tip) and stationary (rub strip) seal components. Wear behavior of inner air seals is more complex and has been omitted from the current model. Other mechanisms such as erosion and contamination which decrease engine efficiency more gradually than seal rubs have also been excluded. At this point, the model assumes that the loads vary

slowly with time and are treated as static. Extension of the model to include dynamic effects is in process.

The analytical procedure (1) described above has been applied in detail by Pratt & Whitney Aircraft (P&WA) to the JT9D-7 engine in the 747 airplane nacelle. Conditions which have been treated include the production engine acceptance test, the airplane flight acceptance test, and an idealized representation of revenue service. Flight loads for the airplane acceptance test and revenue service simulations were provided by the Boeing Commercial Airplane Company (BCAC).

ANALYTICAL MODEL

The basis for the model is the fact that engine performance is strongly dependent on gas-path seal clearances. In essence, the model provides a vehicle for predicting blade tip rub damage caused by structural deformations which occur during flight operation and relates the corresponding enlarged seal clearances to increases in engine thrust specific fuel consumption (TSFC).

The model is used to compute the change in TSFC that results from the sequence of events which defines an engine flight profile or mission. A given flight profile is broken down into a number of short segments, called time points, for which airplane and engine operating conditions are known. Internal and external flight loads that act at each time point give rise to structural deflections which may or may not exceed the local gap between static and rotating seal components. When an interference (rub) is found to occur, damage to both blade tips and rub strips is calculated and added to the clearances available for succeeding time points. After all time points in a given flight profile have been considered, average clearance changes for all stages are computed and combined with performance influence coefficients to produce Δ TSFC values for standard steady-state engine operating conditions such as

(1) Jay, A. and Todd, E. S., "Effect of Steady Flight Loads on JT9D-7 Performance Deterioration," NASA CR-135407, Aug. 1978, pp. 9-15.

sea-level takeoff and cruise. The sequence of steps required to arrive at a solution are shown schematically in figure 1 and are discussed in more detail below.

Flight Profile Definition

The starting point for all deterioration predictions due to flight loads is a description of the sequence of operating conditions or events which comprise an engine mission or flight profile.

The flight profile is divided into a series of aircraft operating conditions (startup, taxi, takeoff, climb, cruise, descent approach, landing, and shutdown), characterized by combinations of aircraft and engine operating parameters (gross weight, altitude, Mach number, rotor speeds, temperatures, pressures, and flows). These parameters are then used in subsequent aerodynamic, thermodynamic, and structural analyses. Aerodynamic and inertial loads acting on the engine at these conditions have been developed by BCAC and are used as input to the analytical model. A description of how these loads were developed is found in reference 1.

Attention has been primarily focused on the airplane acceptance test flight (Table 1) chiefly because the profile is well defined and reasonably controlled. Ground tests and fleet service which precede and follow the flight acceptance test, respectively, have also been included but in a less rigorous fashion. In the simulation of the 747 service experience, it was necessary to change the flight acceptance test profile to include only those maneuvers which are typical of a revenue flight. Airplane stall checks are not part of a 747 revenue flight, so those time points were deleted.

Since the maximum loads encountered during revenue service flights will ultimately exceed the loads experienced by the airplane during flight acceptance testing, a method of accounting for maximum flight loads experienced as a function of flight cycles was necessary. Accordingly, BCAC provided

load exceedance curves for aerodynamic cowl loads and gravitational loads for various numbers of flight cycles. Load exceedance data for pitch and yaw rates was provided by P&WA. These exceedance curves were then used as input to the NASTRAN analytical model to predict performance deterioration of the JT9D engine in the 747 airplane.

Axisymmetric Loads and Deflections

Temperature, pressure, and centrifugal force fields play an important role in determining internal seal clearances. A convenient feature of this set of forces is the common assumption that circumferential variations in these fields are small and, for the purposes of deflection analysis, can be neglected. Another characteristic is that each field varies appreciably in response to changes in power level and requires a transient analysis for proper representation. Specialized computational procedures have been developed to perform the secondary flow, heat transfer, and other analyses that define temperature, pressure, and rotor speed time histories for desired flight profiles. These loads are input to axisymmetric structural analysis programs which generate corresponding histories of relative deflections (gap closures) between static and rotating components of the gas-path seals (fig. 2-A). Combination of the axisymmetric closures with values for the initial build clearances (cold gaps, also assumed to be uniform) then provides the running clearances as functions of time. These clearances are called baseline clearances since they indicate the gaps available for accommodation of additional deflections due to external flight loads.

Asymmetric Loads and Deflections

The second set of structural deformations is related to loads which are not uniformly distributed with respect to the engine centerline. Generally, the set arises from external motions or restraints imposed by the flight environment and is composed of inlet air loads, inertial loads (G and gyro), thrust, and

thrust reverse loads. Asymmetric cowl loads occur as pressure distributions around the inlet which is bolted to the engine (fig. 3). The contribution of these loads to the performance deterioration problem presents a greater challenge than was the case for the previous group. The loads produce asymmetric deflections (fig. 2-D) which may be decomposed into symmetric (fig. 2-C) and antisymmetric components (fig. 2-B) for ease of analysis. This aspect allows only a half finite element model of the JT9D-7 to be used with proper symmetric or antisymmetric boundary conditions applied at the symmetry plane (vertical plane through the engine centerline). These loads produce axial and circumferential variations in engine case deformations that differ significantly from patterns which can be predicted with the classical beam model approach. In order to allow for case ovalization, local distortion around thrust pickups and mount points, and other shell-like effects, a more complex representation than the beam theory is required. While some success in dealing with ovalization effects has been achieved with shell-of-revolution formulations, only the finite element method has been found to provide the modeling flexibility required to obtain accurate deflection solutions. The NASTRAN finite element model of a flight-dressed JT9D-7 engine available from earlier studies (2) was adopted for description of asymmetric structural deflections.

NASTRAN Structural Model

The NASTRAN structural model was jointly developed by P&WA and BCAC and began with an identification of below-the-wing propulsion system substructures, which were provided by each party. Since primary emphasis in the

(2) White, J. L. and Todd, E. S., "Normal Modes Vibration Analysis of the JT9D/747 Propulsion System," J. Aircraft, vol. 15, no. 1, Jan. 1978, pp. 28-32.

study was on behavior of the engine, the wing was not included.

Substructure interfaces were chosen where subassemblies were mechanically joined (i.e., mount points, flanges, etc.). Detailed finite-element models of the engine static structure (cases and bearing support frames), rotors, and thrust yoke were provided by P&WA. Rotors were modeled as beams with discrete masses input directly. BCAC provided the inlet, strut, and tailcone models.

Secondary structural components (fan and core cowls, fan and turbine reversers, and stator assemblies), accessories, and plumbing were included as discrete or distributed masses as appropriate to bring the mass properties of the model to within 5 percent of the actual hardware. The final static model consisted of eight substructures with approximately 11,000 freedoms as shown in figure 4.

Clearance Increases and Resulting Δ TSFC

In order to reduce the labor and time required to manipulate the output data from the NASTRAN program to obtain Δ TSFC values for various flight profiles, a computer program was constructed to interface with the NASTRAN program. This program computes, for all engine stages, the clearance increases and performance deterioration which result from flight load-induced deflections calculated by the NASTRAN program.

The process by which structural deflections are translated into blade-tip/rub-strip damage (local interference) is schematically indicated in figure 5. As already seen (fig. 1), the procedure involves calculations for a sequence of time points selected from the given flight profile. For each time point, the effects of axisymmetric loads (baseline clearances), offset grinds, and rub damage from previous time points are first combined to establish the circumferential variation of clearance that is available for accommodation of nonaxisymmetric structural deformations (fig. 5-A). Asymmetric rotor/case

deflections are then introduced (fig. 5-B), and when the relative closures exceed the available gap, the extent of rub damage is recorded (fig. 5-C). In general, the damage occurs in two forms: circumferentially uniform wear of the blade tips, and local (crescent shaped) machining of the rub strip. The trade-off between blade-tip/rub-strip damage is dictated by the characteristics of the contacting materials and appears in the model through parameters called abrasability factors (figs. 1 and 5). Values are assigned to these parameters on the basis of experimentally determined volume wear ratios for each material pair involved. Then increased clearances caused by shortened blades and the worn rub strip are, in turn, carried forward to appear as increased initial clearances for the next time point. At the end of the cycle, the accumulated damage for each rub strip is circumferentially averaged and added to the accumulated blade-tip wear to provide the average clearance increase for each stage.

The final step to be taken involves conversion of permanent clearance changes for the total cycle to increases in TSFC under standard performance conditions. This is accomplished by simply summing the contributions from each stage, or,

$$\Delta \text{TSFC} = \sum_{\text{All stages } (x = 1 \text{ through } x = 21)} P_x C_x$$

where

P_x performance influence coefficient for a stage

C_x average clearance change for the stage

Influence coefficients which are unique to a particular engine model have been developed for the JT9D-7 engine. These coefficients relate blade-tip/rub-strip average damage to performance loss (ΔTSFC).

RESULTS

Predicted Rub Damage

Results achieved by computer simulation of the JT9D-7/747 airplane acceptance test are shown in Table 2, for the outboard side of the simulated engine only. Predicted values of local damage occur primarily in the fan, low-pressure compressor, and high- and low-pressure turbines, with only minimal damage in the high-pressure compressor. Fan stage damage is primarily sidewise due to the effect of airplane pitch up or down which causes the rotors to move laterally (gyroscopic effect). Similar calculations were performed for 150, 1000, and 3000 flights.

Stage average damages for the various flight cycles, due to the quasi-steady flight loads, are shown in Table 3. These values are obtained by circumferentially averaging the local values. The average damage is linearly converted to Δ TSFC using performance influence coefficients. Such analytically predicted values are shown at the bottom of Table 3 for static sea-level takeoff conditions.

Short-Term Deterioration

Short-term deterioration is that performance deterioration which occurs in an engine due to degradation of tight clearances, as experienced early in the engine cyclic life. This life includes both the flight acceptance test and the early revenue service flight cycles. Early degradation, as previously mentioned, is believed to be due primarily to the effect of flight loads on blade-tip/rub-strip interferences.

A comparison of predicted circumferential average rub damages versus available data on average actual measured values for a service engine (3) is

(3) Bouchard, R. J., Beyerly, W. R., and Sallee, G. P., "Short-Term Performance Deterioration in JT9D-7A (SP) Engine 695743," NASA CR-135431, Sept. 1978.

shown in Table 4. In this case, the predictions for 150 flights are compared to actual values after 141 flights. The comparison shows good agreement for approximately 50 percent of the engine stages. For one stage - the fan stage - good agreement is shown in a comparison of measured and calculated circumferential values, as shown in figure 6. For the other stages, circumferential rub damage distributions do not compare satisfactorily.

The NASTRAN predicted values of the change in static sea-level takeoff TSFC, after the first flight and after 150 flights, are plotted in figure 7 against actual data on short-term deterioration. The excellent agreement of the data tends to confirm that short-term deterioration is primarily a function of load-induced changes in seal clearances.

Long-Term Deterioration

The analytically predicted changes in TSFC for 1, 150, 100, and 3000, flights (Table 3) are compared to actual 747 fleet experience in figure 8. The predicted deterioration results based on quasi-steady flight loads only are lower than the fleet average values. The remaining TSFC deterioration is attributable to erosion, surface roughness, thermal distortions, and dynamic load effects not accounted for in the model. The significant trend observed, however, is that loads are a contributing factor to long-term deterioration as well as short-term deterioration.

Effects of Various Load Types on Performance Deterioration

Using the analytical procedure, the contribution of the various types of flight loads (thrust, aerodynamic, gravitational, and gyroscopic) to engine performance deterioration was explored. Table 5 shows the results of this effort after the engine has undergone 150 flights.

The contribution of thrust to additional damage is zero. The explanation for this is that during the production acceptance test an engine is run to higher thrust levels than it would ordinarily encounter in the flight acceptance test or

service. Any damage occurring due to thrust alone occurs during the production acceptance test with no further damage in the flight acceptance test or revenue service flights due to thrust only. During operation, thrust contributes to closure but there is enough available clearance (previous damage, baseline clearance, and offset grinds) to prevent additional damage due to thrust alone.

Air loads contribute heavily to overall engine deterioration. In this case, for 150 flights, air loads account for approximately 90 percent of the overall "loads contribution" to deterioration. Gravitational (G) loadings effect only the two high-pressure turbine stages from a damage standpoint. These stages contribute to the overall deterioration of the engine by approximately 7 percent of the Δ TSFC. Gyroscopic loadings primarily affect the fan stage of the engine from the standpoint of damage, because the fan is a massive overhung stage with large rotary inertia. In terms of deterioration, the effects of gyro loadings amount to approximately 3 percent of the total Δ TSFC.

CONCLUSIONS

An analytical procedure for assessing the effects of the flight loads on engine performance deterioration has been developed and applied to predict changes in TSFC for the JT9D-7/747 installation. Good correlation between predicted and observed values for Δ TSFC confirm the basic assumption that load-induced seal rubs have a predominant effect on short-term performance deterioration. Results also indicate that such loads are contributors to long-term deterioration.

The analytical procedure provides for the detailed description of loads and deflections as they vary with time for arbitrary flight profiles and thereby permits the effects of individual loads to be isolated for evaluation. For the 747/JT9D-7 propulsion system, studies of this kind indicate that air loads (inlet lift) are the dominant factor; inertia loads (G and gyro) are of

secondary importance, and thrust loads do not alone contribute to performance losses after the production engine acceptance test.

Usefulness of the procedure as a diagnostic tool for understanding the major cause of early performance deterioration (rub-induced clearance changes) has been demonstrated. This procedure is also being used to study and compare concepts for minimizing engine performance deterioration. These concepts include: engine design features such as mounts, case stiffening, optimum bearing placement and active clearance control; and installation design features to relieve engine loads.

Further refinement of the analytical procedure will be accomplished in the future by incorporating the results of a dynamic loads analysis and a steady-state load test program on a JT9D flight engine using X-ray techniques along with laser proximity probes to measure stage clearances changes.

NOMENCLATURE

C_x	average clearance change for stage x
G	gravity, gravitational field
HPC	high-pressure compressor
HPT	high-pressure turbine
LPC	low-pressure compressor
LPT	low-pressure turbine
M	Mach number
i_x	performance influence coefficient for stage x
SSLTO	steady sea-level takeoff
TSFC	thrust specific fuel consumption
V_s	airplane stall velocity

REFERENCES

1. Jay, A. and Todd, E. S., "Effect of Steady Flight Loads on JT9D-7 Performance Deterioration," NASA CR-135407, 1978, pp. 9-15.
2. White, J. L. and Todd, E. S., "Normal Modes Vibration Analysis of the JT9D/747 Propulsion System," Journal of Aircraft, Vol. 15, No. 1, Jan. 1978, pp. 28-32.
3. Bouchard, R. J., Beyerly, W. R., and Saltee, G. P., "Short-Term Performance Deterioration in JT9D-7A (SP) engine 695743," NASA CR-135431, 1978.

TABLE 1. - FLIGHT PROFILE PARAMETERS FOR
AIRPLANE ACCEPTANCE TEST

Altitude		M _n	Flight condition	Description
ft	m			
0	0	0.186	100	Takeoff roll
0	0	.214	101	Takeoff rotation
3,000	914	.401	102	Early climb
17,500	5,330	.617	103	Mid climb
35,000	10,670	.860	104	High Mach cruise
35,000	10,670	.770	105	Low Mach cruise
32,000	9,750	.920	106	Maximum Mach
27,500	8,380	.720	107	In-flight shutdown
20,000	6,100	.830	108	Maximum q
17,000	5,180	.340	109	1.3 V _s , 0° flaps
17,000	5,180	.340	110	1.3 V _s , 10° flaps
17,000	5,180	.340	111	1.3 V _s , 30° flaps
17,000	5,130	.340	112	Early descent
3,000	914	.240	113	Approach, 20° flaps
0	0	.271	114	Touchdown
0	0	-----	115	Thrust reverse

TABLE 2. - LOCAL DAMAGE MAP FOR AIRPLANE ACCEPTANCE TEST - PREDICTED VALUES

	LPC						HPC						HPT						LPT					
	Fan	2	3	4	5	6	7	8	9	10	11	12	13	14	15	1	2	3	4	5	6			
0°	7 (0.18)	1 (0.03)	52 (1.32)	73 (1.85)												3 (0.08)	6 (0.15)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	9°		
15°	9 (0.23)		38 (0.97)	53 (1.35)												3 (0.08)	6 (0.15)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	12°		
30°	10 (0.25)		3 (0.05)	7 (0.18)												3 (0.08)	6 (0.15)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	24°		
45°	24 (0.6)															3 (0.08)	6 (0.15)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	36°		
60°	37 (0.94)		7 (0.18)	16 (0.41)		3 (0.08)										3 (0.08)	6 (0.15)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	48°		
75°	45 (1.14)		11 (2.8)	20 (0.51)		5 (0.13)					1 (0.03)					3 (0.08)	8 (0.20)	1 (0.03)	3 (0.08)	4 (0.10)	8 (0.20)	60°		
90°	47 (1.19)		8 (0.08)	8 (0.20)												3 (0.08)	12 (0.30)	2 (0.05)	3 (0.08)	4 (0.10)	8 (0.20)	72°		
105°	16 (0.41)		6 (0.15)	15 (0.38)												3 (0.08)	16 (0.41)	3 (0.08)	4 (0.10)	5 (0.13)	12 (0.30)	84°		
120°			11 (0.28)	20 (0.51)												3 (0.08)	18 (0.46)	3 (0.08)	5 (0.13)	7 (0.18)	14 (0.36)	96°		
135°		2 (0.05)	10 (0.25)	16 (0.41)												4 (0.10)	19 (0.48)	4 (0.10)	6 (0.15)	9 (0.23)	17 (0.43)	108°		
150°		4 (0.10)	5 (0.13)	7 (0.18)												5 (0.13)	21 (0.53)	4 (0.10)	7 (0.18)	10 (0.25)	18 (0.46)	120°		
165°		5 (0.13)	1 (0.03)	8 (0.20)												5 (0.13)	21 (0.53)	4 (0.10)	7 (0.18)	10 (0.25)	15 (0.36)	132°		
180°	16 (0.25)	6 (0.15)	1 (0.03)	13 (0.33)												4 (0.10)	20 (0.51)	3 (0.08)	7 (0.18)	10 (0.25)	18 (0.46)	144°		
																4 (0.10)	18 (0.46)	3 (0.08)	6 (0.15)	9 (0.23)	17 (0.43)	156°		
																4 (0.10)	18 (0.46)	3 (0.08)	6 (0.15)	9 (0.23)	17 (0.43)	168°		
																4 (0.10)	18 (0.46)	3 (0.08)	6 (0.15)	9 (0.23)	17 (0.43)	180°		

Outboard side of engine

TABLE 3. - AVERAGE RUB DAMAGE PREDICTIONS FOR
747 AIRPLANE SERVICE ENGINES IN MILS (mm)

Stage	1st Flight	150 Flights	1000 Flights	3000 Flights
Fan	10 (0.25)	31 (0.79)	51 (1.3)	58 (1.47)
2LPC	2 (0.05)	4 (0.10)	6 (0.15)	6 (0.15)
3LPC	14 (0.36)	15 (0.38)	17 (0.43)	17 (0.43)
4LPC	21 (0.53)	23 (0.58)	25 (0.63)	25 (0.63)
5HPC	-----	-----	1 (0.03)	1 (0.03)
6HPC	-----	-----	2 (0.05)	2 (0.05)
7HPC	-----	-----	-----	-----
8HPC	-----	-----	-----	-----
9HPC	-----	-----	-----	-----
10HPC	-----	-----	-----	-----
11HPC	-----	-----	1 (0.03)	1 (0.03)
12HPC	-----	-----	-----	-----
13HPC	-----	-----	-----	-----
14HPC	-----	-----	-----	-----
15HPC	-----	-----	-----	-----
1HPT	3 (0.08)	7 (0.18)	8 (0.20)	8 (0.20)
2HPT	10 (0.25)	14 (0.36)	16 (0.41)	16 (0.41)
3LPT	1 (0.03)	1 (0.03)	1 (0.03)	1 (0.03)
4LPT	4 (0.10)	3 (0.08)	3 (0.08)	3 (0.08)
5LPT	5 (0.13)	5 (0.13)	5 (0.13)	5 (0.13)
6LPT	10 (0.25)	10 (0.25)	11 (0.28)	11 (0.28)
% Δ Tsfc (SSLTO)	1.13	1.65	1.86	2.09

TABLE 4. - RUB DAMAGES - ANALYTICAL
PREDICTION VERSUS MEASURED
VALUES IN MILS (mm)

Stage	150 Flight prediction	Measured on test engine after 141 flights
Fan	31 (0.79)	43 (1.09)
2LPC	4 (0.10)	18 (0.46)
3LPC	15 (0.38)	6 (0.15)
4LPC	23 (0.58)	27 (0.69)
5HPC	-----	1 (0.03)
6HPC	-----	1 (0.03)
7HPC	-----	1 (0.03)
8HPC	-----	3 (0.08)
9HPC	-----	2 (0.05)
10HPC	-----	14 (0.36)
11HPC	-----	6 (0.15)
12HPC	-----	18 (0.46)
13HPC	-----	7 (0.18)
14HPC	-----	19 (0.48)
15HPC	-----	15 (0.38)
1HPT	7 (0.18)	8 (0.20)
2HPT	14 (0.36)	23 (0.58)
3LPT	1 (0.03)	7 (0.18)
4LPT	8 (0.08)	3 (0.08)
5LPT	5 (0.13)	3 (0.08)
6LPT	10 (0.25)	5 (0.13)
% Δ Tsfc (SSLTO)	1.65	1.2

TABLE 5. - AVERAGE DAMAGE IN MILS (mm) AND TSFC INCREASE

AT 150 FLIGHTS - LOAD CONTRIBUTION

Stage	Thrust only	Thrust + airloads	Thrust + airloads + G loadings	Thrust + airloads + G loadings + gyro loadings
Fan	---	20 (0.51)	20 (0.51)	31 (0.79)
2LPC	---	1 (0.03)	2 (0.05)	4 (0.10)
3LPC	---	15 (0.38)	15 (0.38)	15 (0.38)
4LPC	---	23 (0.58)	23 (0.58)	23 (0.58)
5HPC	---	---	---	---
6HPC	---	---	---	---
7HPC	---	---	---	---
8HPC	---	---	---	---
9HPC	---	---	---	---
10HPC	---	---	---	---
11HPC	---	---	---	---
12HPC	---	---	---	---
13HPC	---	---	---	---
14HPC	---	---	---	---
15HPC	---	---	---	---
1HPT	---	5 (0.13)	7 (0.18)	7 (0.18)
2HPT	---	12 (0.30)	14 (0.36)	14 (0.36)
3LPT	---	1 (0.03)	1 (0.03)	1 (0.03)
4LPT	---	3 (0.08)	3 (0.08)	3 (0.08)
5LPT	---	5 (0.13)	5 (0.13)	5 (0.13)
6LPT	---	10 (0.25)	10 (0.25)	10 (0.25)
% Δ TSFC	0	1.5	1.61	1.65

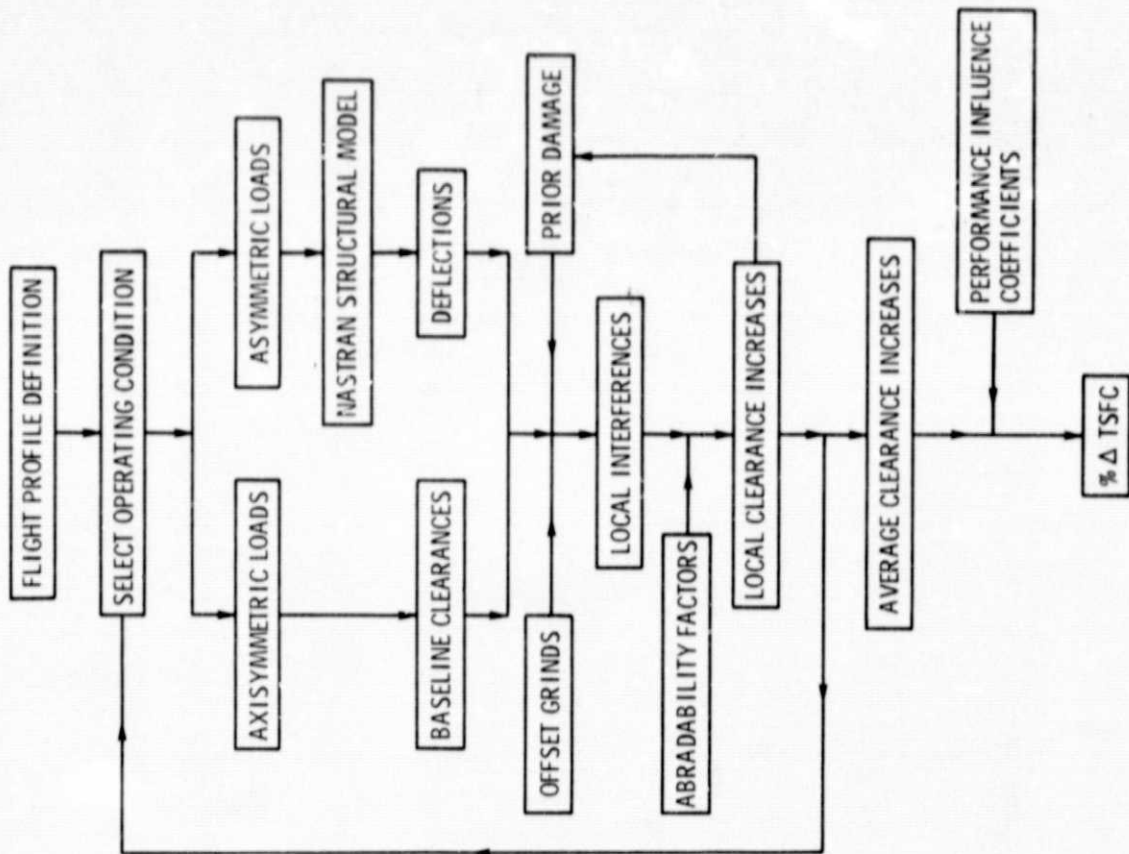


Figure 1. - Flow chart for analytical model.

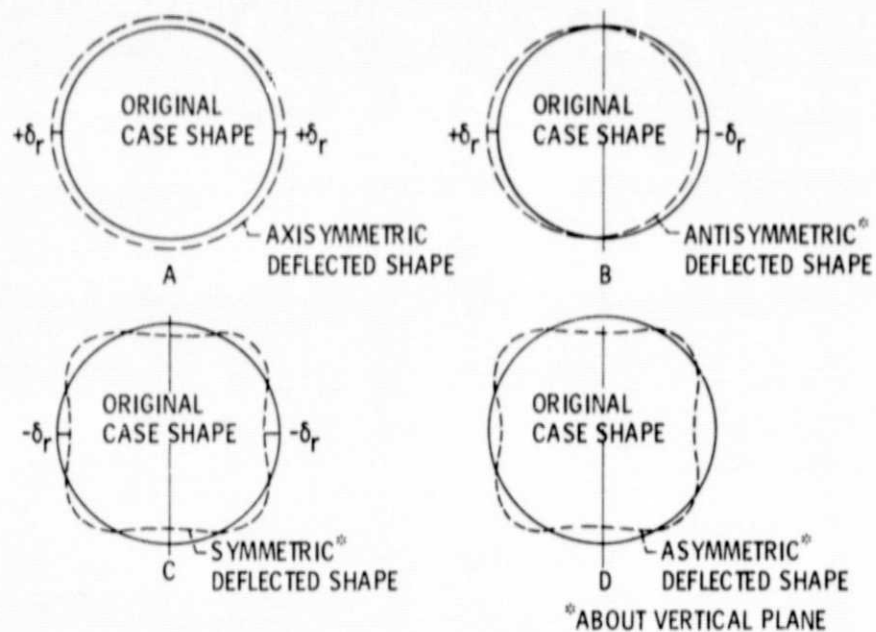


Figure 2. - Illustrative case deflections.

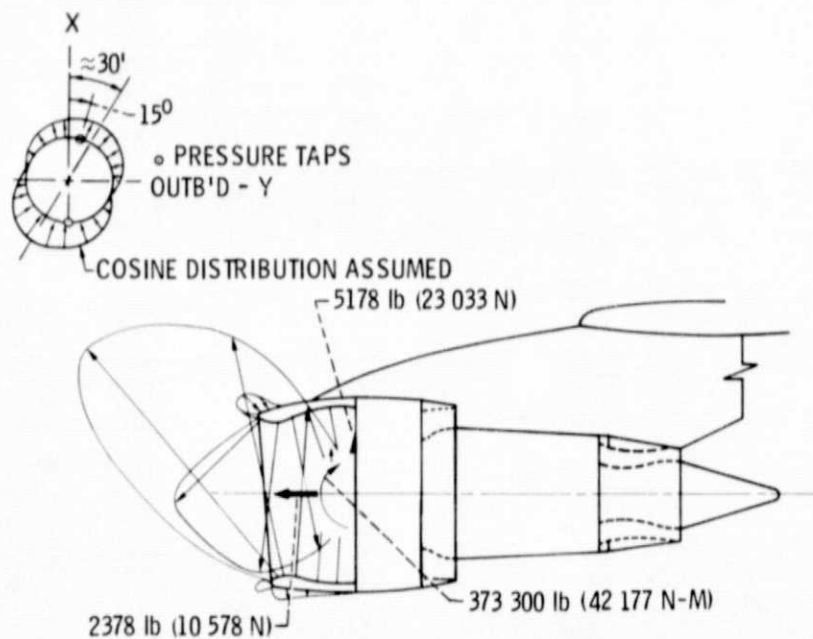


Figure 3. - JT9D-7 pressure loads. Flight test condition 101 (max takeoff).

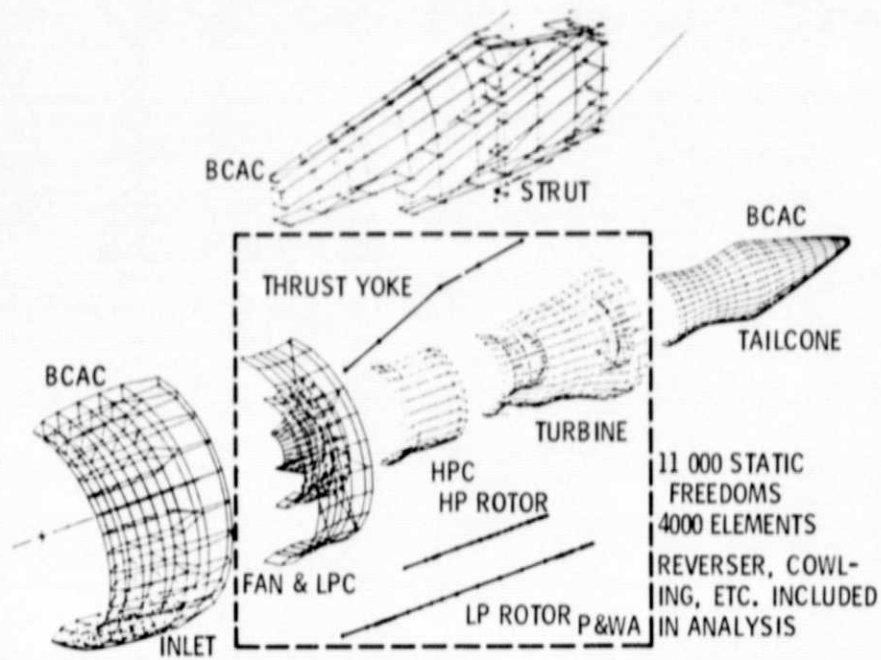


Figure 4. - JT9D-7/747 propulsion system substructures and responsibilities.

- $D_B + D_R = \delta$
- ABRADABILITY FACTORS, D_B/δ AND D_R/δ , DEPEND ON VOLUME WEAR RATIO OF MATERIALS INVOLVED

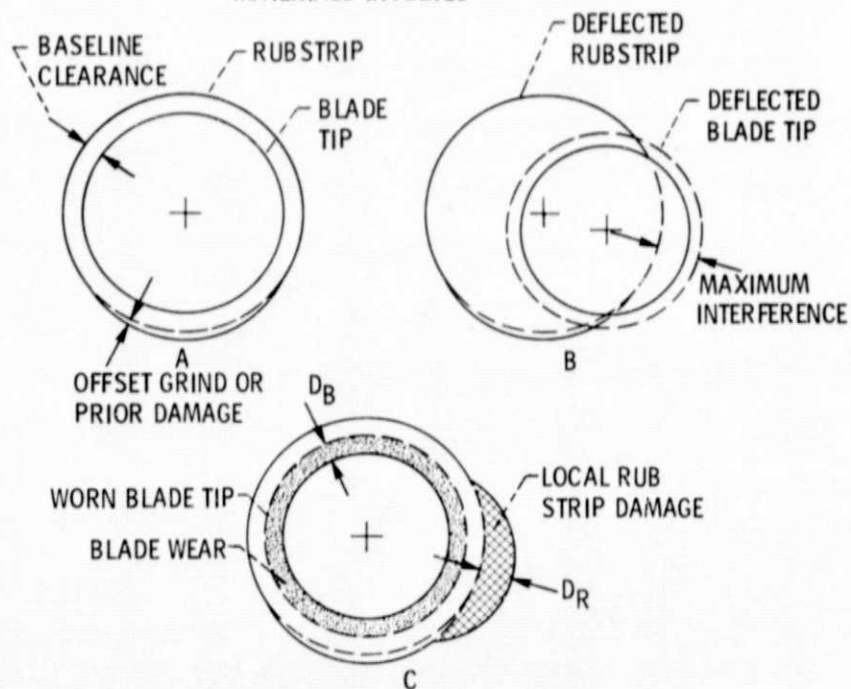


Figure 5. - Schematic of blade-tip/rub-strip damage calculation.

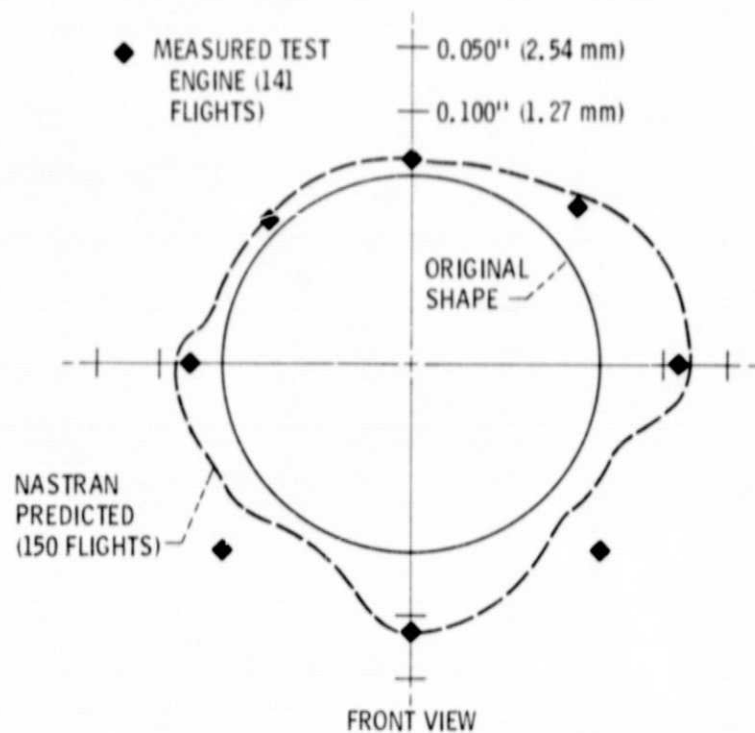


Figure 6. - Fan rub patterns. Analytical/experimental correlation.

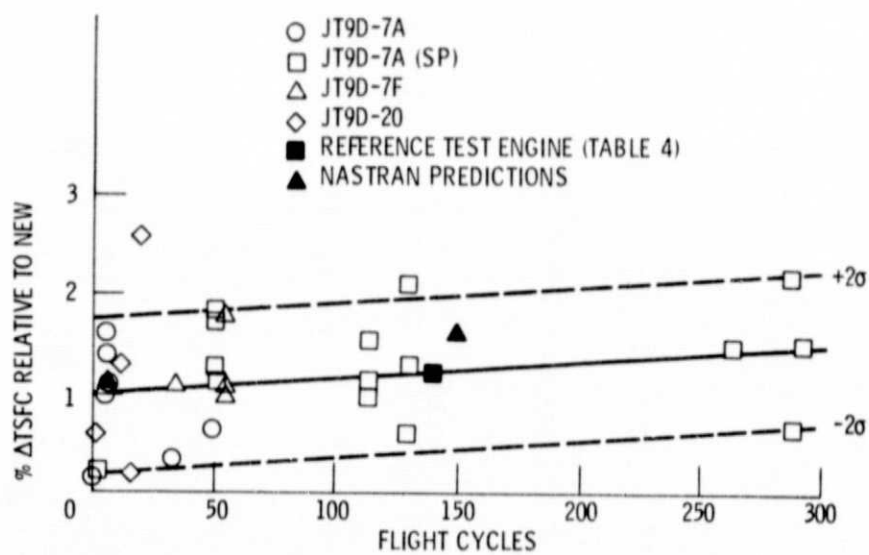


Figure 7. - Short term deterioration.

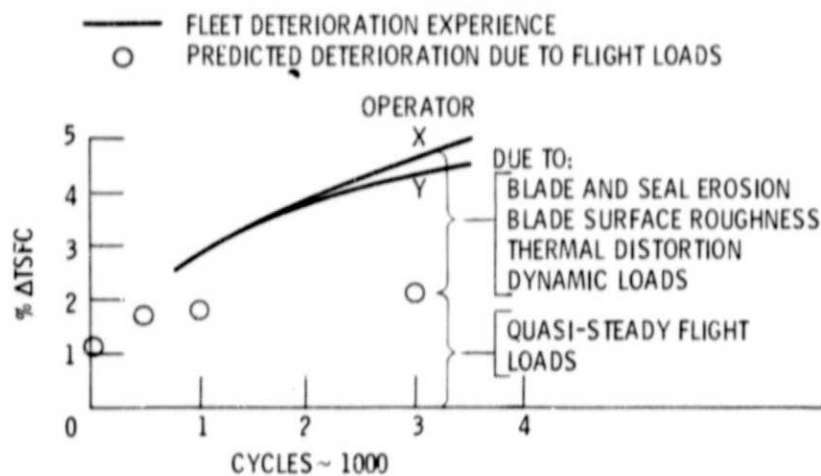


Figure 8. - Comparison of NASTRAN predicted deterioration with average fleet JT9D-7 engine experience.